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Life cycle assessment of gas power with CCS - a study showing the environmental benefits of system integration

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Abstract

The aim of the study has been to compare the environmental impacts of four different gas power plant scenarios, both with and without carbon capture and storage (CCS). The functional unit is 1 TWh electricity generated and delivered to the grid. Life cycle assessment (LCA) methodology based on the ISO-standards 14040/44 was used. The study concludes that the CCS scenarios have reduced impacts for the global warming potential category only. However, process integration is the best CCS option of the scenarios analysed. One obvious way to reduce the environmental effects from the CCS system is to reduce the efficiency penalty, the steam consumption for regenerating amines and the emissions of MEA, ammonia and acetaldehyde. Compression, pipeline transport, injection and storage of CO_2 has almost negligible impacts for all of the impact categories analysed.

It is still important to find more optimal design options. Focus should be on process integration, since this scenario has proved to be the best of the CCS scenarios analysed.

Keywords: Gas power; carbon capture and storage (CCS); life cycle assessment (LCA); post-combustion; system integration

1. Introduction

Statoil has for many years worked to develop technology and processes to meet the climate challenge connected to extraction and use of fossil-based energy carriers. The debate regarding CO_2 capture, transport and storage has mainly focused on technology and economy, and a complete environmental analysis for a Norwegian case has not been available. This is why Statoil in 2007 decided to make a Life Cycle Assessment (LCA) of a possible future Tjeldbergodden gas power plant case, including CO_2 capture, transport and storage (CCS). The strength of an LCA is the holistic perspective from 'cradle to grave', which means that the analysis includes all the activities through the whole value chain, and the inclusion of several environmental impact categories.

Phase I of the project started in spring 2007. In phase II two additional scenarios were analysed. The project was finnished in autumn 2009 and has given useful information regarding improvements of the design of the CCS system.

Ostfold Research is a private research company in Norway, with high level competence on holistic environmental assessments. Ostfold Reseach has previously carried out life cycle inventory studies of platform-based production of oil and gas in the Norwegian sector and LCAs of gas power plants at Kårstø and Kollsnes.

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2. Aim and functional unit

The aim of the study was to compare the environmental impacts of four different gas power plant scenarios, including one scenario based on system integration, and by this give input to future strategic choices in Statoil. The model developed can be the basis for scenarios and could be used as an ecodesign tool for Statoil in their CCS development process. The functional unit is 1 TWh electricity generated at Tjeldbergodden gas power plant and delivered to the grid.

3. System boundaries and project design

The study was carried out using life cycle assessment (LCA) methodology based on the ISO-standards 14040/44. The following environmental impact categories were included: global warming potential, acidification potential, eutrophication potential, photochemical ozone creation potential and cumulative energy demand. Four scenarios were analysed:

- Reference Gas power plant without CCS
- CCS-1 Gas power plant with CCS, separate gas fuelled steam boiler for amine regeneration
- CCS-2 Gas power plant with CCS, separate biofuelled steam boiler for amine regeneration
- CCS-3 Gas power plant with CCS, steam from steam turbine for amine regeneration (system integration)

No integration between the CO_2 capture process and the power plant was included in the scenarios CCS-1 and CCS-2, except for the electricity consumption in the capture process, which was assumed to be delivered by the gas power plant. Due to the low integration between the power plant and the capture process, these scenarios were supposed to be 'worst case scenarios' for electricity production with CCS at Tjeldbergodden. In scenario CCS-3 the power plant and the CO_2 capture process were closely integrated by steam delivery from the power plant to the CO2 capture plant.

In all four scenarios, natural gas from the Heidrun field was used in a combined cycle process. The CO_2 capture process was based on post-combustion decarbonisation using MEA (monoethanolamine) absorbtion. After the capture process, the CO_2 was transported in a 150 km pipeline to storage at the Heidrun licence area. A simplified flowsheet of the gas power plant scenarios is shown in Figure 1.

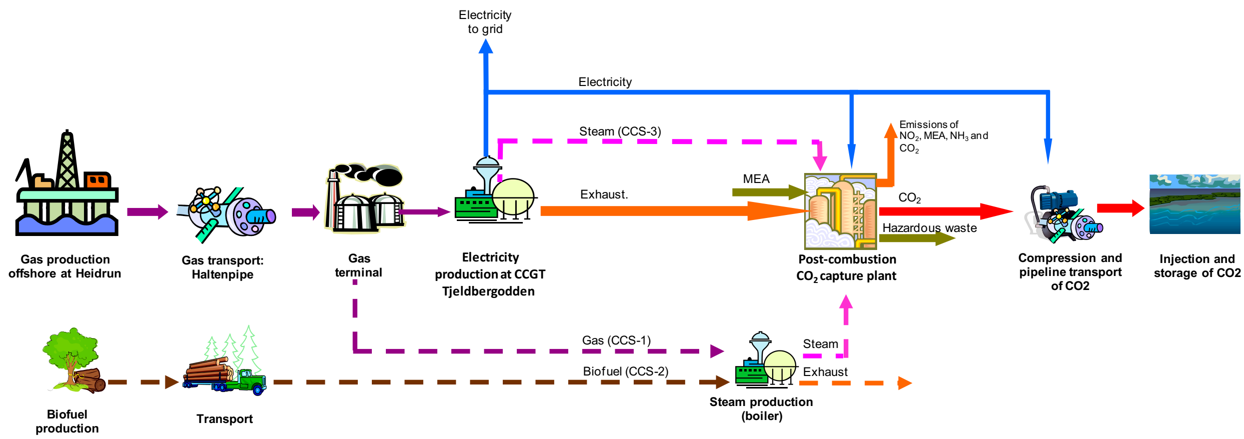


Figure 1 Simplified flow sheet of the Tjeldbergodden gas power plant case with CO_2 capture, transport and storage (four scenarios)

The power plant was designed with two gas turbines of 262 MWnominal each in addition to one steam turbine of 328 MWnominal. The nett power production was 832 MW for the reference scenario and 789 MW for the scenarios CCS-1 and CCS-2. For scenario CCS-3 the net power was 702 MW. The nett efficiency of the power plant was hence 59.1% in the reference scenario, 44.8% in the CCS-1 and CCS-2 scenarios and 50.0% in the CCS-3 scenario.

It was assumed that the CO_2 capture fraction will be 90%, or 2.1 million tonnes per year. The capture facility will have emissions of CO_2, NO_2, MEA and NH_3 in addition to waste containing MEA, which will be treated as hazardous waste. Construction and demolition of infrastructure such as pipelines, platform, terminal, buildings, turbines and process equipment were included in the analysis.

4. Data sources

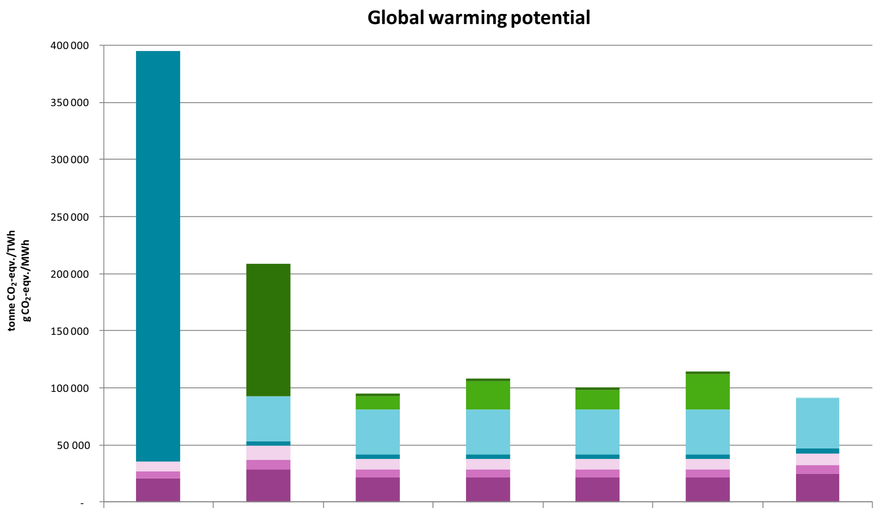
Design information and technical specifications for a suggested Statoil power plant, capture facilities and CO_2 transport system at Tjeldbergodden have been available for this study [1, 2]. In addition, data for a future capture facility at Naturkraft's power plant at Kårstø have been used [3]. Literature data from the IEA Greenhouse Gas R&D programme and Statistics Norway have also been useful [4, 5]. Details about the data used and the system boundaries are given in Modahl et al. 2009 [6].

5. Impact assessment results

In order to show the different types of trends in results, the authors have chosen to show detailed results for GWP and eutrophication potential. A summary of the relative results (compared to the reference scenario) is included as a diagramme in chapter 5.3.

5.1 Global Warming Potential

Figure 2 shows the contribution to the global warming potential (GWP) by the different power plant scenarios. The figure shows that the best result is achieved by the CCS-3 scenario where the global warming potential has decreased by 77% compared to the reference scenario. The next best result is achieved by use of biofuel for amine regeneration (scenarios CCS-2a/b/c/d) where the global warming potentials have decreased by 76% - 71%, while use of gas for amine regeneration (scenario CCS-1) only reduces the global warming potential by 47%.



	Reference scenario	Scenario CCS-1 Gas boiler	Scenario CCS-2a Biofuel boiler	Scenario CCS-2b Biofuel boiler	Scenario CCS-2c Biofuel boiler	Scenario CCS-2d Biofuel boiler	Scenario CCS-3 Process integration
External steam production for amine regeneration	-	115 793	2 485	2 485	2 485	2 485	-
Extraction, transport and treatment of biofuel	-	-	11 401	25 015	17 098	31 077	-
Compression, pipeline transport, injection and storage of CO2	-	137	137	137	137	137	154
Post-combustion CO2 capture	-	39 080	39 080	39 080	39 080	39 080	43 860
Electricity production at CCGT Tjeldbergodden	359 805	4 254	4 254	4 254	4 254	4 254	4 775
Gas treatment at terminal	8 567	11 839	9 034	9 034	9 034	9 034	10 139
Gas transport Haltenpipe	6 405	8 851	6 754	6 754	6 754	6 754	7 580
Gas production offshore at Heidrun	20 607	28 478	21 731	21 731	21 731	21 731	24 389

Figure 2 Global warming potential for electricity from different power plant scenarios (tCO_2-eqv./TWh delivered to the grid).

In the reference scenario, the dominant phase is the electricity production, which contributes with approximately 91% of the global warming potential. This burden is caused by CO_2 emissions from the combustion of gas. Gas production offshore contributes with 5% and gas transport and gas treatment at the terminal contribute with 2% each.

In the CCS-1 scenario, the most important phase is the external steam production for amine regeneration, which contributes with 56% of the global warming potential. The flue gas from combustion of gas in the steam production phase is not captured, hence the high CO_2 emissions. The CO_2 capture phase contributes with 19% and the gas production offshore 14%. In the CO_2 capture phase, the global warming potential is due to the fact that only 90% of the CO_2 emissions from the power plant are captured. Production and transport of chemicals used (for example MEA) does not contribute much to the total. The small amount of greenhouse gasses from the electricity production phase is caused mostly by emissions of CH_4 (and CO) from the combustion process. Gas treatment at the terminal and gas transport contribute 6% and 4% respectively. The compression, pipeline transport, injection and storage phase is almost negligible.

In the CCS-2 scenarios, the most important phase is CO_2 capture (34% - 41%), followed by gas production offshore (19% - 23%), but also extraction, transport and treatment of biofuel plays an important role (12% - 27%). It is the transportation part which dominates this phase. The burden is less in the scenario with Norwegian biofuel transported a short distance (Scenario 2a), then comes the scenario with biofuel from the Baltic states (Scenario 2c) and Norway/long distance (scenario 2b), while the scenario which uses biofuel from Canada (Scenario 2d) has the highest burdens when it comes to global warming potential.

In the CCS-3 scenario, the most important phase is also CO_2 capture (48%), followed by gas production offshore (27%). Gas transport, gas treatment and electricity production contribute with 8%, 11% and 5% respectively.

The global warming potential from gas production offshore, gas transport and gas treatment at the terminal have all increased by 38% in the CCS-1 scenario when compared to the reference scenario. There are two reasons for this:

- the efficiency penalty in the electricity production phase due to consumption of electricity for the CO2 capture process and for compression/pipeline transport of CO_2, which means that more gas is needed to produce the same amount of electricity to the grid (5.5% points).
- extra gas has to be produced, transported and treated for steam production for amine regeneration (32.5% points).

In the CCS-2 scenarios, the global warming potential for the same three phases (gas production, gas transport and gas treatment) have increased by 5% compared to the reference scenario. This is because of the efficiency penalty in the electricity production phase due to the electricity consumption for the CO_2 capture and compression/pipeline transport of CO_2.

In the CCS-3 scenario, the global warming potential for these three phases (gas production, gas transport and gas treatment) have increased by 18% compared to the reference scenario due to the efficiency penalty in the electricity production phase, which is caused by:

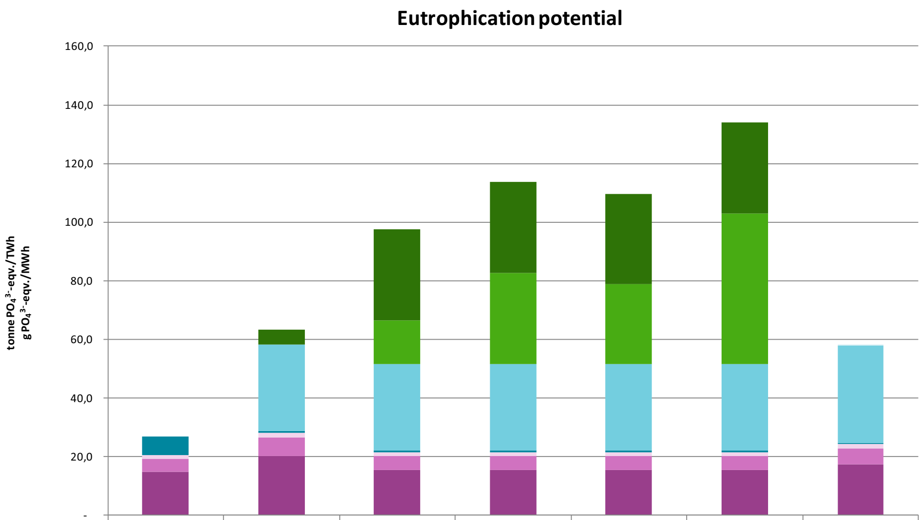
- The electricity consumption for the CO_2 capture process and compression/pipeline transport of CO_2 (5.5% points).
- The loss of thermal work due to withdrawal of low pressure steam for regeneration of solvent (12% points).

This loss of thermal work is also the reason why the CCS-3 scenario has higher global warming potential than the scenarios CCS-1 and CCS-2 in the electricity production phase, the CO_2 capture phase and the compression/pipeline transport of CO_2 phase.

The results from the LCA analysis also show that the global warming potential is completely dominated by emissions from operation, and that emissions from production, transport and waste treatment of infrastructure is almost negligible. The authors have also used the results to calculate the 'CO_2 avoidance efficiency', which is defined as the amount of CO_2–eqv. avoided compared to the amount of CO_2 stored [7]. The average CO_2 avoidance efficiency in the analysed scenarios is 80%.

5.2 Eutrophication potential

Figure 3 shows the contribution to the eutrophication potential by the different power plant scenarios. The figure shows that the best result is achieved by the reference scenario, and that the 'least bad' CCS scenario is scenario CCS-3 where the eutrophication potential has increased by 117% compared to the reference scenario. In scenario CCS-1 the eutrophication potential has increased by 137% and in the scenarios CCS-2a/b/c/d the eutrophication potentials have increased by 266% - 403%. The eutrophication potential is completely dominated by emissions from operation for all the scenarios analysed.



	Reference scenario	Scenario CCS-1 Gas boiler	Scenario CCS-2a Biofuel boiler	Scenario CCS-2b Biofuel boiler	Scenario CCS-2c Biofuel boiler	Scenario CCS-2d Biofuel boiler	Scenario CCS-3 Process integration
External steam production for amine regeneration	-	5,0	30,9	30,9	30,9	30,9	-
Extraction, transport and treatment of biofuel	-	-	15,0	31,1	27,2	51,4	-
Compression, pipeline transport, injection and storage of CO2	-	0,1	0,1	0,1	0,1	0,1	0,1
Post-combustion CO2 capture	-	29,5	29,5	29,5	29,5	29,5	33,1
Electricity production at CCGT Tjeldbergodden	6,3	0,5	0,5	0,5	0,5	0,5	0,5
Gas treatment at terminal	1,2	1,7	1,3	1,3	1,3	1,3	1,4
Gas transport Haltenpipe	4,5	6,3	4,8	4,8	4,8	4,8	5,4
Gas production offshore at Heidrun	14,6	20,2	15,4	15,4	15,4	15,4	17,3

Figure 3 Eutrophication potential for electricity from different power plant scenarios (tPO_4^{3-}-eqv./TWh delivered to the grid).

In the reference scenario, the dominating phase is gas production offshore, which contributes with 55% of the eutrophication potential. Gas transport and the electricity production phase contributes with 17% and 24% respectively, while gas treatment at the terminal contributes with 5% only.

In the CCS-1 scenario, the two most important phases for eutrophication potential are the CO_2 capture phase and gas production offshore, which contributes with 47% and 32% respectively. In the CO_2 capture phase, the eutrophication potential is mostly caused by the emissions of NOx (10% of the total), ammonia (16 % of the total) and MEA (10% of the total). These NOx emissions come originally from the combustion process in the electricity production stage (assumed unchanged), and the ammonia and MEA emissions are due to the capture process itself. Gas transport contributes with 10% of the eutrophication potential, external steam production for amine regeneration 8% and the gas treatment at terminal phase is responsible for 3%. The small eutrophication potential connected with the electricity production phase is caused by the NOx cleaning process (emission of ammonia) and production of power plant infrastructure. The contribution from compression, pipeline transport, injection and storage phase is almost negligible.

In the CCS-2 scenarios, the eutrophication potentials are dominated by the use of biofuel for amine regeneration (extraction, transport and treatment of biofuel and external steam production for amine regeneration). In the scenario with shortest transportation distance (CCS-2a), these two phases together contribute with 47% of the eutrophication potential, and it is the external steam production phase (combustion of wood) that is largest. The longer the distance for transporting biofuel, the larger the eutrophication potential, and in scenario CCS-2d these two phases together contribute with as much as 61% of the total eutrophication potential. The total eutrophication potential of scenario CCS-2d is 37% higher than scenario CCS-2a.

In the CCS-3 scenario, the most important phase is CO_2 capture (57%), followed by gas production offshore (30%). Gas treatment at terminal, gas transport and electricity production contribute with 9%, 2% and 1% respectively.

5.2 Summary of impacts analysed

The main impact assessment results are shown in Table 1 and the relative impacts for the different power plant scenarios are shown in Figure 4.

Table 1 Impact assessment results for the analysed power plant scenarios

	tonne CO_2-eqv./TWh	tonne SO_2-eqv./TWh	tonne PO_4^{3-} -eqv./TWh	tonne C_2H_4-eqv./TWh	TWh LHV/TWh
	g CO_2-eqv./MWh	g SO_2-eqv./MWh	g PO_4^{3-} -eqv./MWh	g C_2H_4-eqv./MWh	kWh LHV/kWh
Scenario	**Global warming potential**	**Acidification potential**	**Eutrophication potential**	**Photochemical ozone creation potential**	**Cumulative energy demand**
Reference scenario	395 400	148	26.6	4.3	1.6
Scenario CCS-1 Gas boiler	208 400	275	63.1	87.1	2.3
Scenario CCS-2a Biofuel boiler	94 900	379	97.4	98.8	2.2
Scenario CCS-2b Biofuel boiler	108 500	453	113.6	112.4	2.3
Scenario CCS-2c Biofuel boiler	100 600	543	109.6	10.3	2.3
Scenario CCS-2d Biofuel boiler	114 600	806	133.9	127.5	2.3
Scenario CCS-3 Process integration	90 900	240	57.8	87.4	1.9

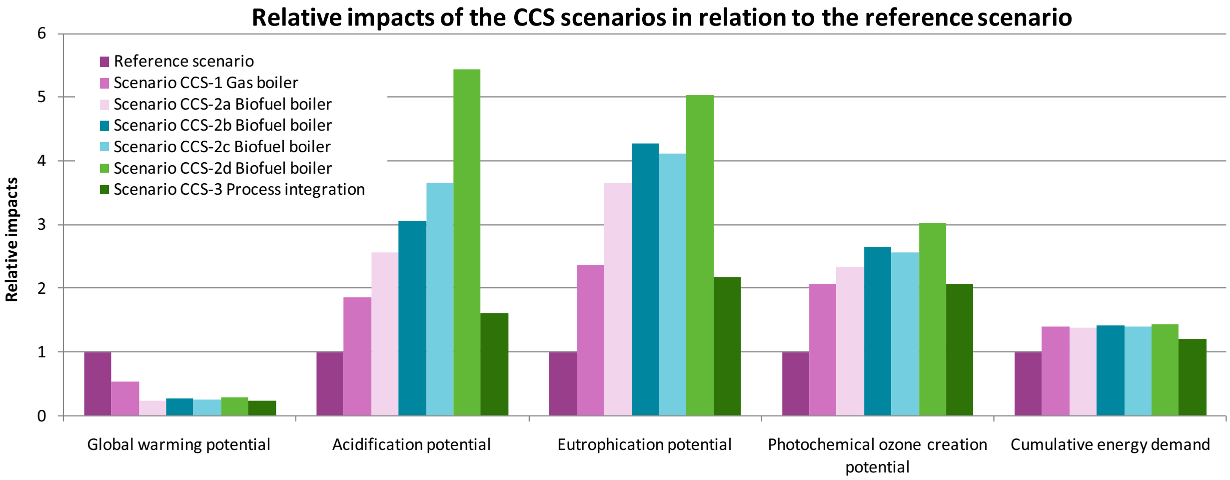


Figure 4 Relative impacts of the CCS scenarios in relation to the Reference Scenario.

The trend is clear: the CCS scenarios have reduced impacts for the global warming potential category only. The total reduction in CO_2 equivalent emissions is 47% for the CCS-1 scenario (gas boiler), 71% - 76% for the CCS-2 scenarios (biofuel boiler) and 77% for the CCS-3 scenario (process integration) when compared with the reference scenario. These results are in line with LCA results found in literature for CCS of a combined electricity and H_2 production plant using natural gas as fuel [8]. The average CO_2 avoidance efficiency in the analysed scenarios are 80%.

It is possible to improve the global warming potential for scenario CCS-1 by capturing the flue gasses from the external steam production for amine regeneration, but the result could never be as good as scenario CCS-3, which is the ‘process integration limit’ for this scenario. The global warming potential results for the CCS-2 scenarios could possibly be even better than the CCS-3 scenario if the biological CO_2 in the flue gas from the external steam production also was captured.

The impacts for the CCS scenarios are higher than for the reference scenario for all the other impact categories analysed, and the ‘least bad’ CCS-scenario is scenario CCS-3. The increased impact is caused by:

- Emissions from the capture process itself (ammonia, MEA and acetaldehyde).
- The efficiency penalties due to:
  - Consumption of electricity for the CO2 capture process and for compression/pipeline transport of CO2, which means that more gas is needed to produce the same amount of electricity to the grid.
  - Withdrawal of low pressure steam for regeneration of solvent, which leads to loss of thermal work in the power plant (applies only for scenario CCS-3).
- Production, transport, treatment and combustion of:
  - Gas (scenario CCS-1)
  - Biofuel (scenario CCS 2a/b/c/d)

  to produce steam for amine regeneration.

Construction of infrastructure, including production of materials and waste treatment of these at their ‘end-of-life, is generally insignificant for both the reference scenario and the CCS scenarios. Compression, pipeline transport, injection and storage of CO_2 has also almost negligible impacts for all of the impact categories analysed.

6. Conclusions and further work

The main findings are summarised below:

- The CCS scenarios have reduced impacts for the global warming potential category only. However, CCS-3 (process integration) is the best CCS option of the scenarios analysed.
- Storing one tonne of CO_2 does not equal one tonne of CO_2 avoided.
- One obvious way to reduce the environmental effects from the CCS system is to reduce the efficiency penalty, the steam consumption for regenerating amines and the emissions of MEA, ammonia and acetaldehyde. Compression, pipeline transport, injection and storage of CO_2 has almost negligible impacts for all of the impact categories analysed.
- It is still important to find more optimal design options. Focus should be on the CCS-3 scenario (process integration), since this scenario has proved to be the best of the CCS scenarios analysed.

This study has chosen not to include impact categories concerning toxic effects due to the large uncertainties in the input data material. In the comming period, the project will focus on degradation products from MEA, include toxicity models and on weighting the results.

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